Int. J. on Recent Trends in Engineering and Technology, Vol. 8, No. 2, Jan 2013

A Three-to-Five-Phase Matrix Converter BasedFive-Phase Induction Motor Drive System

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***Abstract*-This paper presents a five-phase induction motor drive system fed from a three-to-five-phase matrix converter. This is a new concept of generating variable voltage and variable frequency five-phase output using a special matrix converter. This matrix converter is proposed recently which transform the available three-phase supply to five-phase supply. Simple carrier-based PWM scheme with enhanced approach is employed to control the output of the matrix converter. Enhanced approach is utilized so as to increase the output voltage magnitude of the three-to-five-phase matrix converter. The motor is controlled in constant *v/f* mode. Simulation study is carried out for excitation, acceleration, loadingand reversing transients. High quality dynamics are observed.**

***Index Terms*—Carrier-based PWM, Five-phase, Matrix Converter**

I. Introduction

Three-phase Induction motors have well known advantages of simple construction, reliability, ruggedness, low maintenance and low cost which has led to their wide spread use in many industrial applications. The major problem of this machine is their complicated control for speed regulation in industrial drive applications [1-7]. However, with the advent of cheap and fast switching power electronics devices not only the control of induction machine became easier and flexible but also the number of phases of machine became a design parameter. Multi-phase machines (more than three-phases) are found to possess several advantages over three-phase machines such as lower torque pulsation [8-10], higher torque density [11-13], fault tolerance [14-16], better stability [17-18] and lower current ripple [19]. Thus multi-phase order machines are normally considered for niche application areas such as ship propulsion, 'more electric aircraft', electric/hybrid electric vehicles etc. Detailed reviews on the research on multi-phase machines are presented in [20-24]. The induction motor control methods can be broadly classified into scalarand vector control. In the scalar control only the magnitude and frequency of voltage, current and flux linkage space vectors are controlled. In contrast in vector control not only magnitude and frequency but also instantaneous positions of voltage, current and flux space vectors are controlled. Thus in vector control scheme the controller acts on the position of the space vectors and provides their correct orientation for both steady state and transient condition. Recently scalar control of a five-phase induction machine is presented in [5] and the field oriented control for five-phase machine isillustrated in [25-26].This paper focuses on the development of open-loop constant *v/f* control scheme of a five-phase induction motor with the power source as a novel three-phase to five-phase matrix converter. Matrix converter is nowadays considered in many applications including electric drive [7], [27-28]. The major hindrance in the wide acceptance of this power converter topology is their complex control. With the advent of the carrier-based PWM scheme for such topology, their practical realization became highly simplified [29]. This paper proposes for the first time a five-phase induction motor drive system fed using a special matrix converter and this is the major novelty of the paper.

II. Drive Control Scheme

In numerous industrial applications, the dynamic performance of the drive is not so important especially where sudden change in speed is not required. In such cases the cheap solution is to use open-loop or closed-loop constant *v/f* control scheme. A block diagram representation of this control technique is depicted in Fig. 1. The block with dashed line is applicable in conjunction with closed-loop *v/f* control. The basic principle behind this control strategy is to keep the flux constant under all operating conditions. The control algorithm calculates the voltage amplitude, proportional to the command speed value, and the angle is obtained by the integration of this speed. Theseinformation are required to implement space vector PWM of the inverter feeding the motor drive system. The reference speed ω^* determines the inverter frequency which simultaneously defines the reference voltage required. The voltage boost is then added to this voltage signal to implement the constant *v/f* scheme (this is especially important for low speed operation). This scheme is well documented in the literature for three-phase drive system. and a detailed discussion is presented in [1-4]. The same is not true for a five-phase drive system except for [5] where detailed model of a five-phase induction motor drive is presented for open-loop constant *v/f* control. This paper

DOI: 01.IJRTET.8.2.94_503

Int. J. on Recent Trends in Engineering and Technology, Vol. 8, No. 2, Jan 2013

focuses on a five-phase drive system with the feeding power converter is replaced from the conventional five-phase voltage source inverter to a non-square matrix converter.
The control law is given by equation (1) where V_0 is called voltage boost. The control law is shown in Fig. 2. This is required to offset the effect of the stator resistance drop especially at low speed. The resulting torque-speed characteristics using this control law approaches those obtainable with true constant flux operation.

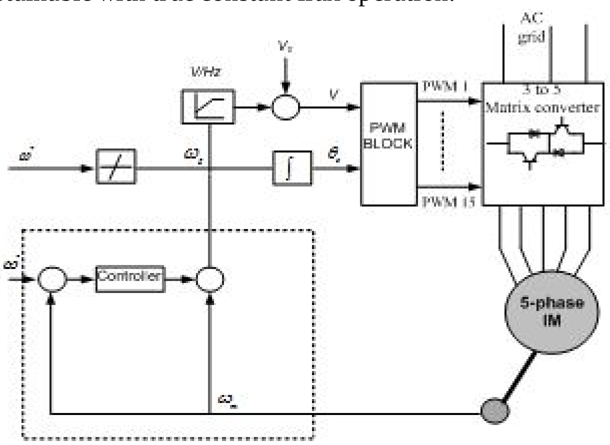

Fig. 1. Constant *V/f* control scheme for a five-phase drive

$$V = k\left(\frac{V_n}{f_n}\right)f + V_0 \qquad (1)$$

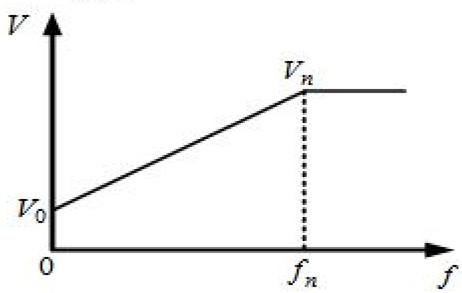

Fig. 2. Illustration of control law for a five-phase drive.

III. Three-to-Five phase Matrix converter Control

The power circuit topology of a three-phase to five-phase matrix converter is illustrated in Fig. 3. There are five legs with each leg having three bidirectional power switches connected in series. Each power switch is bidirectional in

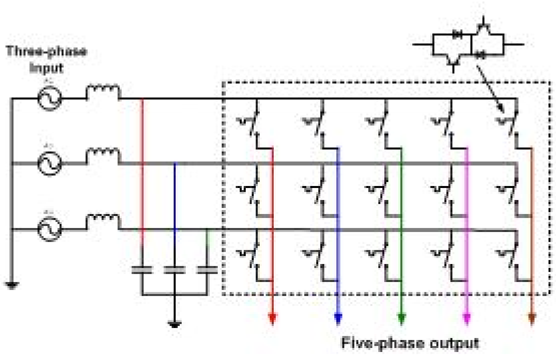

Fig. 3. Power Circuit topology of three-phase to five-phase matrix converter

nature with anti-parallel connected IGBTs and diodes. The input is similar to a three-phase to three-phase matrix converter having LC filters and the output is five-phases with 72Ú phase displacement between each phases.The load to the matrix converter is assumed as star-connected five-phase ac machine.

Switching function is defined as S_{jk} = {1 for closed switch, 0 for open switch}, j = {a,b,c} (input), k= {A,B,C,D,E} (output). The switching constraint is $S_{ak} + S_{bk} + S_{ck} = 1$.

IV. Simulink Model of the Drive System

This section describe the step by step development of simulink model to implement constant *v/f* control scheme.The purpose here is to replicate the model in such way as to matches the real time DSP/FPGAimplementation requirement. In case of real time implementation 3.3 V input to the DSP/ FPGA corresponds to the rated speed of the motor. Thus by simply augmenting the control voltage, the speed of the motor can be varied from zero to the rated value (only base speed is considered here) keeping constant *v/f*ratio. The user operating frequency corresponding to the reference speed is provided to the PWM block of the matrix converter, here it represented as a block termed as “Carrier based PWM’.

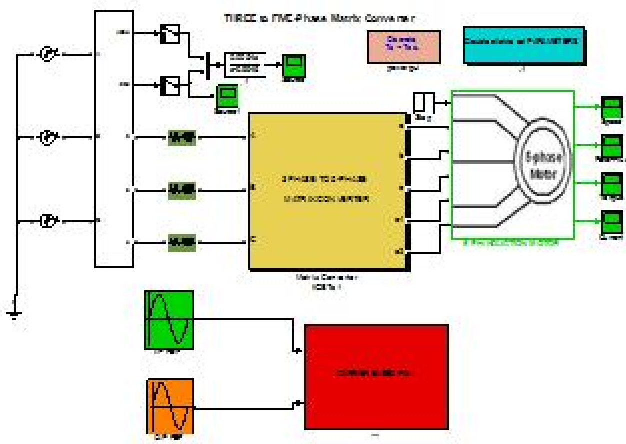

Fig. 4. Simulink model of constant *v/f* control of five-phase Induction Motor.

The working prinsiple of the carrier based scheme is illustrated in the next sub-section. The PWM generation block generate appropriate gating signals. The gating signals thus generated is fed to IGBT bidirectional power modules which ultimelty run the induction machine. The simulation blocks is depicted in Fig. 4.

A. Carrier-based PWM-Matrix Converter Control

The major problem with the matrix converter is their complex control due to large number of power semiconductor switches. The complexity increases with the increase in the number of semiconductor switches. Recently, very simple control is presented for a three-phase to five-phase matrix converter, called ‘Carrier based PWM’. This technique is analogous to the carrier based PWM scheme of a five-phase voltage source inverter, however, the gate signal generation method is different.

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The input voltages can be given as

$$v_a = \vec{V}\sin(\omega t),$$
$$v_b = \vec{V}\sin(\omega t - 2\pi/3), \quad (2)$$
$$v_b = \vec{V}\sin(\omega t - 4\pi/3)$$

The five-phase output voltage duty ratios should be calculated in such a way that output voltages remains independent of input frequency, thus duty ratios of output phase A are chosen as

$$d_{aA} = k_A\cos(\omega t - \rho),$$
$$d_{bA} = k_A\cos(\omega t - 2\pi/3 - \rho), \quad (3)$$
$$d_{cA} = k_A\cos(\omega t - 4\pi/3 - \rho)$$

Therefore the phase 'A' output voltage can be obtained by using the above duty ratios as

$$v_A = k_A\vec{V}[\cos(\omega t)\bullet\cos(\omega t - \rho)$$
$$+\cos(\omega t - 2\pi/3)\bullet\cos(\omega t - 2\pi/3 - \rho) \quad (4)$$
$$+\cos(\omega t - 4\pi/3)\bullet\cos(\omega t - 4\pi/3 - \rho)]$$

In general equation (4) can be written as

$$v_A = \frac{3}{2}k_A\vec{V}\cos(\rho) \quad (5)$$

In equation (4), $\cos(\rho)$ term indicates that the output voltage is affectedby ρ. Thus, the output voltage v_A is independent of the input frequency and only depends on the amplitude $\vec{V}$ of the input voltage and k_A is a reference output voltage time-varying modulating signal for the output phase 'A' with the desired output frequency ω_o. The 5-phase reference output voltages can be represented as

$$k_A = m\cos(\omega_o t),$$
$$k_B = m\cos(\omega_o t - 2\pi/5),$$
$$k_C = m\cos(\omega_o t - 4\pi/5),$$
$$k_D = m\cos(\omega_o t - 6\pi/5),$$
$$k_E = m\cos(\omega_o t - 8\pi/5),$$

(6)

Therefore, from (5), the output voltage in phase-Ais

$$v_A = \left[\frac{3}{2}k_A\vec{V}\cos(\rho)\right]\cos(\omega_o t) \quad (7)$$

In the above explanation, duty-ratios become negative which are not practically realizable. For the switchesconnected to output phase-A, at any instant, the condition $0 \le d_{aA}, d_{bA}, d_{cA} \le 1$ should be valid. Therefore, offset duty ratios should to be added to the existing duty-ratios, so that the net resultant duty-ratios of individual switches are always positive. Furthermore, the offset duty-ratios should be added equally to all the output phases to ensure that the effect of resultant output voltage vector produced by the offset duty-ratios is null in the load. That is, the offset duty-ratios can only add the common-mode voltages in the output.Considering the case of output phase-A

$$d_{aA} + d_{bA} + d_{cA} = k_A\cos(\omega t - \rho) +$$
$$k_A\cos(\omega t - 2\pi/3 - \rho) \quad (8)$$
$$+ k_A\cos(\omega t - 4\pi/3 - \rho) = 0$$

The modified duty ratios for output phase A, thus obtained as;

$$d_{aA} = D_a(t) + k_A\cos(\omega t - \rho),$$
$$d_{bA} = D_b(t) + k_A\cos(\omega t - 2\pi/3 - \rho), \quad (9)$$
$$d_{cA} = D_c(t) + k_A\cos(\omega t - 4\pi/3 - \rho)$$

If k_A, k_B, k_C, k_D, k_E are chosen to be 5-phase sinusoidal references as given in Eqn. 6, the input voltage capability is not fully utilized for output voltage generation. To overcome this, an additional common mode term equal to $\{\max(k_A, k_B, k_C, k_D k_E) + \min(k_A, k_B, k_C, k_D k_E)\}/2]$ is added as in the carrier-based PWM principle as implemented in two-level inverters. Thus the amplitude of $k_A, k_B, k_C, k_D k_E$ can be enhanced from 0.5 with 0.5257.The duty ratio is given as

$$D_a(t) = |0.5\cos(\omega t - \rho)|$$
$$D_b(t) = |0.5\cos(\omega t - 2\pi/3 - \rho)| \quad (10)$$
$$D_b(t) = |0.5\cos(\omega t - 4\pi/3 - \rho)|$$

Further detail of this scheme is available in [29].

V. Results and Discussion

The simulation is carried out to implement the open-loop constant *v/f* control technique using the developed simulation model. The simulation is done to investigate the acceleration, loading and reversing dynamics of the drive system. The reference speed of 1500 rpm is given initially then the reference speed is step down to 1200 rpm,at t=0.6 sec. Rated load of 8.33 Nm is applied to the motor at t = 1 sec. Finally the reference speed is step down to -1200 rpm at t=1.2sec.under rated loading condition. The resulting drive behavior is presented in Fig. 5. The actual speed follows the reference speed very well as illustrated in the top trace of Fig. 5a, under no-load condition.It takes nearly 0.5 sec. for motor to reach the steady-state condition as evident from all the traces. There is a slight undershoot in the speed when it is reduced to 1200 rpm, as evident from torque response as well in Fig. 5b. However, the speed quickly settles to the commanded value.The loading rejection capability for open-loop constant *v/f* control scheme, of five-phase induction machine is studied. The speed drops by nearly 90 rpm due to application of load, and it remains at the same value as there is no speed correction controller. The transient torque reaches nearly 2.5 times the rated value under no-load acceleration transient. Reversing dynamics is also seen as typical of an open-loop induction

DOI: 01.IJRTET.8.2.94_503

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motor drive. Further analysis is done for the input side (grid side) current. The input side voltage and filtered current for one phase is shown in Fig. 6a. The input side unity power factor operation is illustrated in Fig. 6b. It is to be noted that the Fig. 6b is a small portion of Fig. 6a. The filtered input current is completely sinusoidal as illustrated from its spectrum shown in Fig. 7. The spectrum shows only fundamental component without any low order harmonic. This is the major advantage of a matrix converter fed drive when compared to an inverter fed drive.

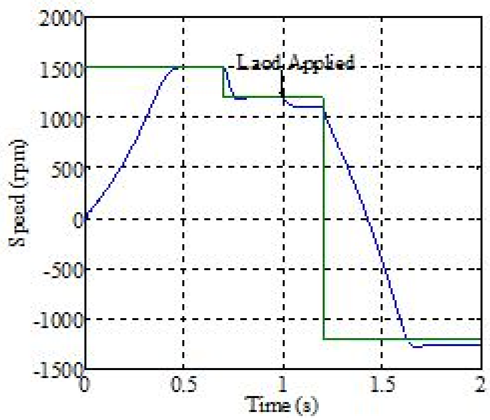

Fig. 5a.

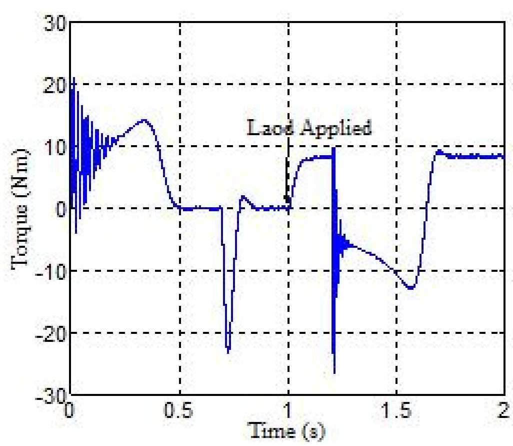

Fig. 5b.

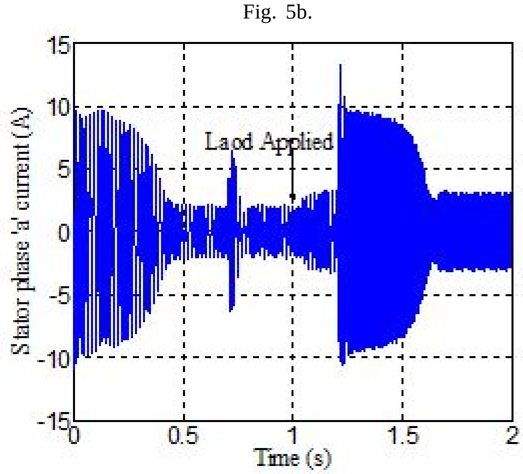

Fig. 5c.

Fig. 5. Responses for a open-loop constant *v/f* control of a five-phase Induction motor drive using Matrix Converter.

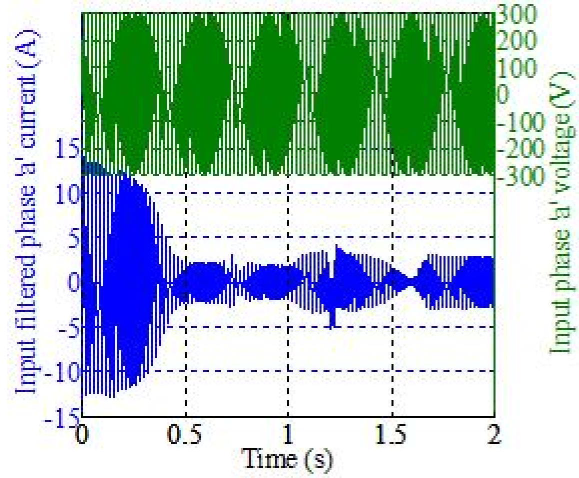

Fig. 6a.

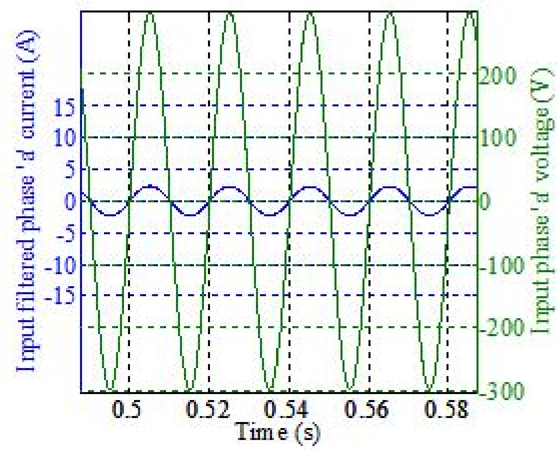

Fig.6b.

Fig. 6. Input/Grid side voltage and current.

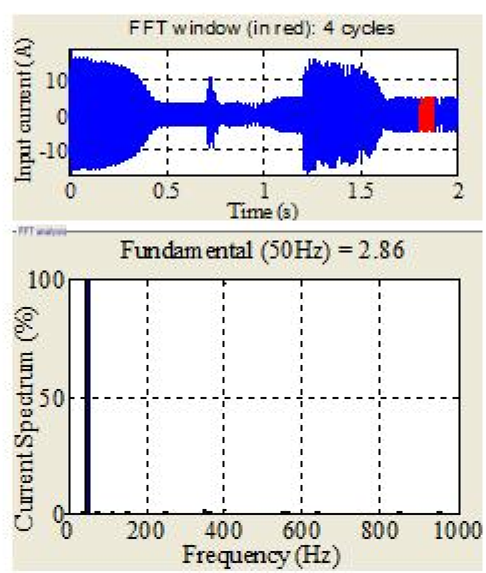

Fig. 7. Input/Grid side current and its spectrum.

Conclusion

This paper presents a novel five-phase induction motor drive system fed using a non-square three-phase to five-phase matrix converter. The control of matrix converter is

DOI: 01.IJRTET.8.2.94_503

presented. The drive behavior is similar to inverter fed drive. The major advantage of the drive system, is sinusoidal input side current and unity power factor operation. This is a special feature which makes this topology very attractive.

ACKNOWLEDGMENT

This publication was made possible by an NPRP (NPRP 4 - 152 - 2 - 053) grant from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

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APPENDIX 1: R_S = 10 ohm, R_r = 6.3 ohm, L_s = L_r = 0.46 H, L_m = 0.4 H, P = 4.(Appendix should be referred in the text)

DOI: 01.IJRTET.8.2. 94_503